HL-LHC MQXF results and lessons learnt

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on behalf of the MQXF collaboration

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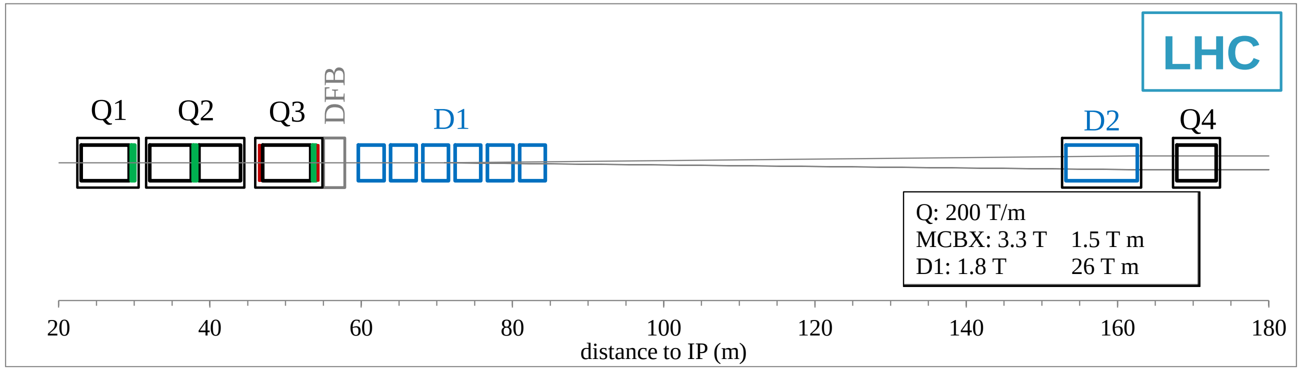
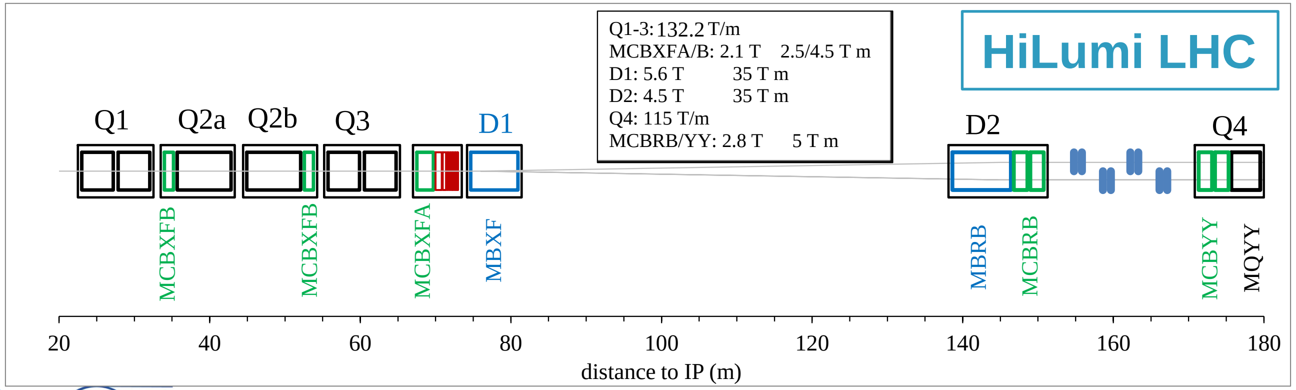
Outline

- Introduction
- Short model program MQXFS
- AUP 4.2 m long MQXFA
- CERN 7.2 m long MQXFB
- Conclusions

Introduction
HL-LHC Interaction Region

- New inner triplet quadrupole
  - Larger aperture to reduce the beam size: from 70 to 150 mm
  - Nb-Ti to Nb_3Sn → only 8 m longer than in the LHC (23 m → 31 m)

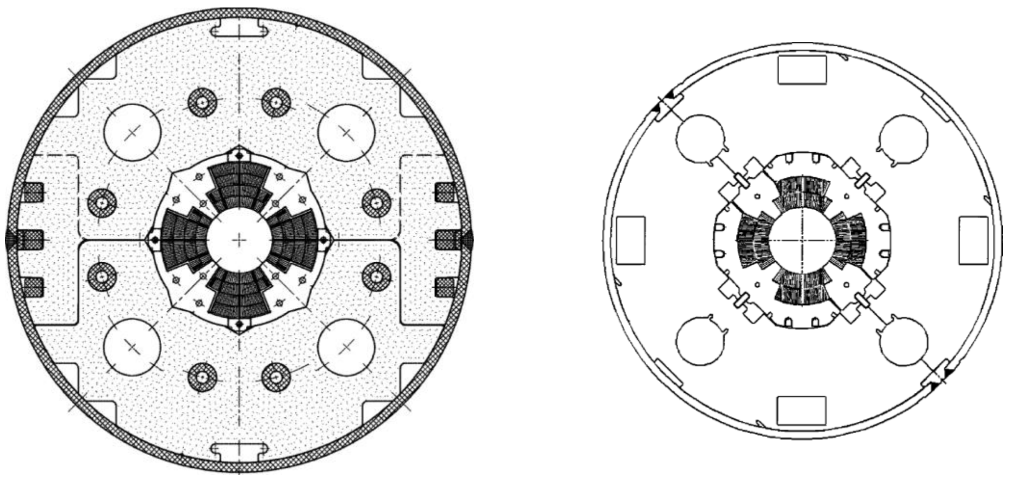




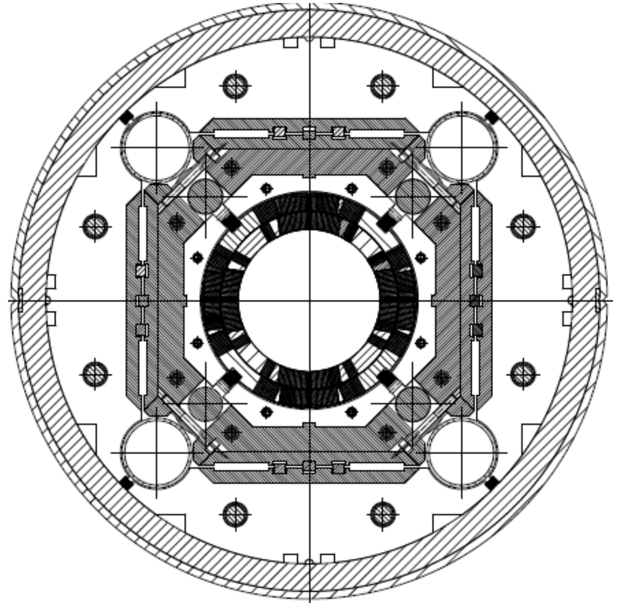
Introduction
from LHC to HL-LHC low-β quadrupoles

- Everything significantly increased
  - strand…cable…coil…structure
- From 70 mm to 150 mm aperture
- From Nb-Ti at 8.6 T to Nb_3Sn at 11.3 T
- ~4 times the e.m. forces in straight section and in the ends

LHC low-β quadrupoles

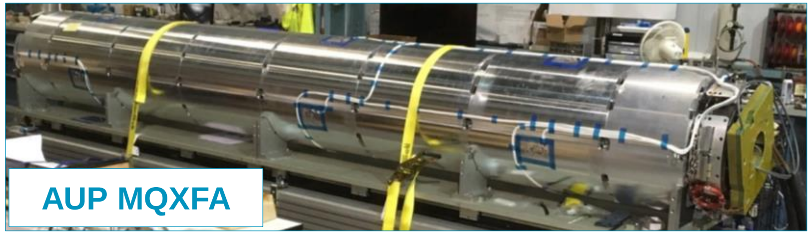


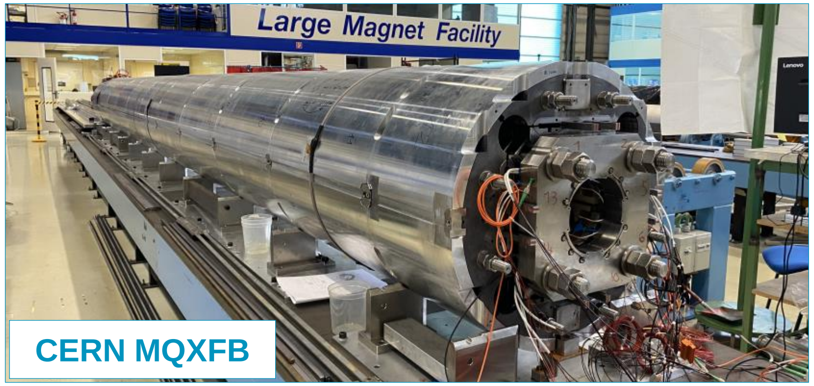
HL-LHC low-β quadrupoles



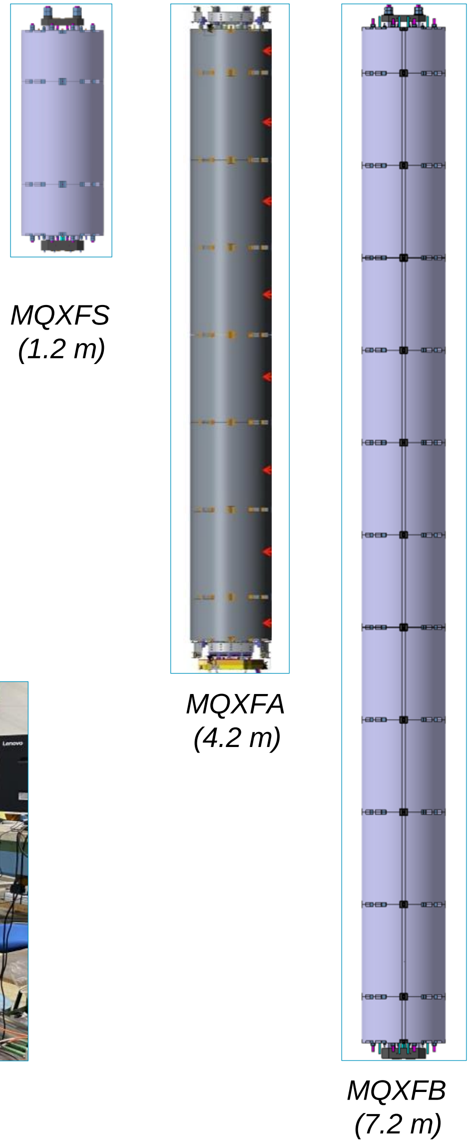
Introduction
HiLumi low-β quadrupole MQXF

- Joint CERN-LARP short model development program (MQXFS) to validate the design



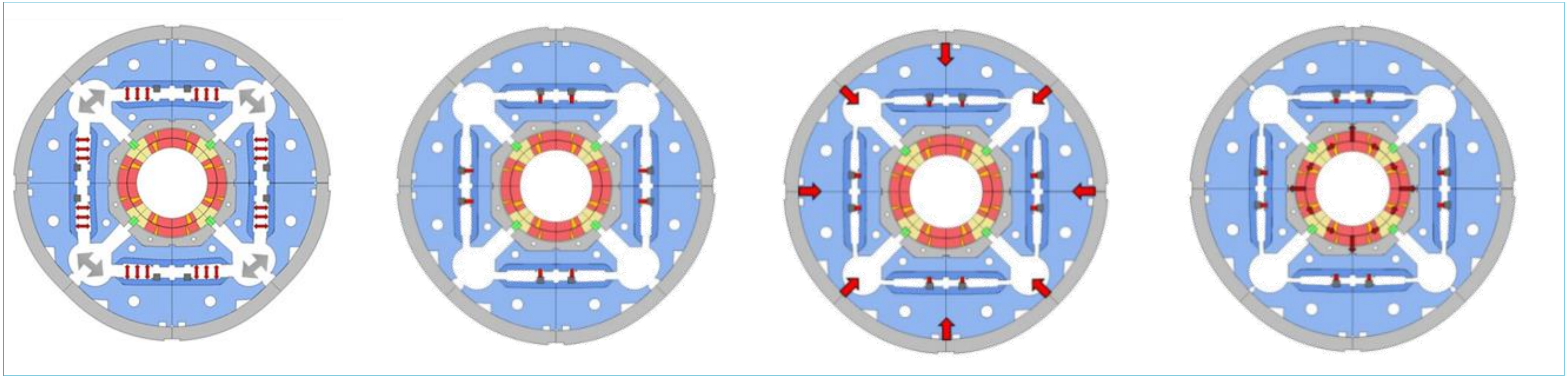


- Different lengths, same design, very similar assembly procedure and loading target



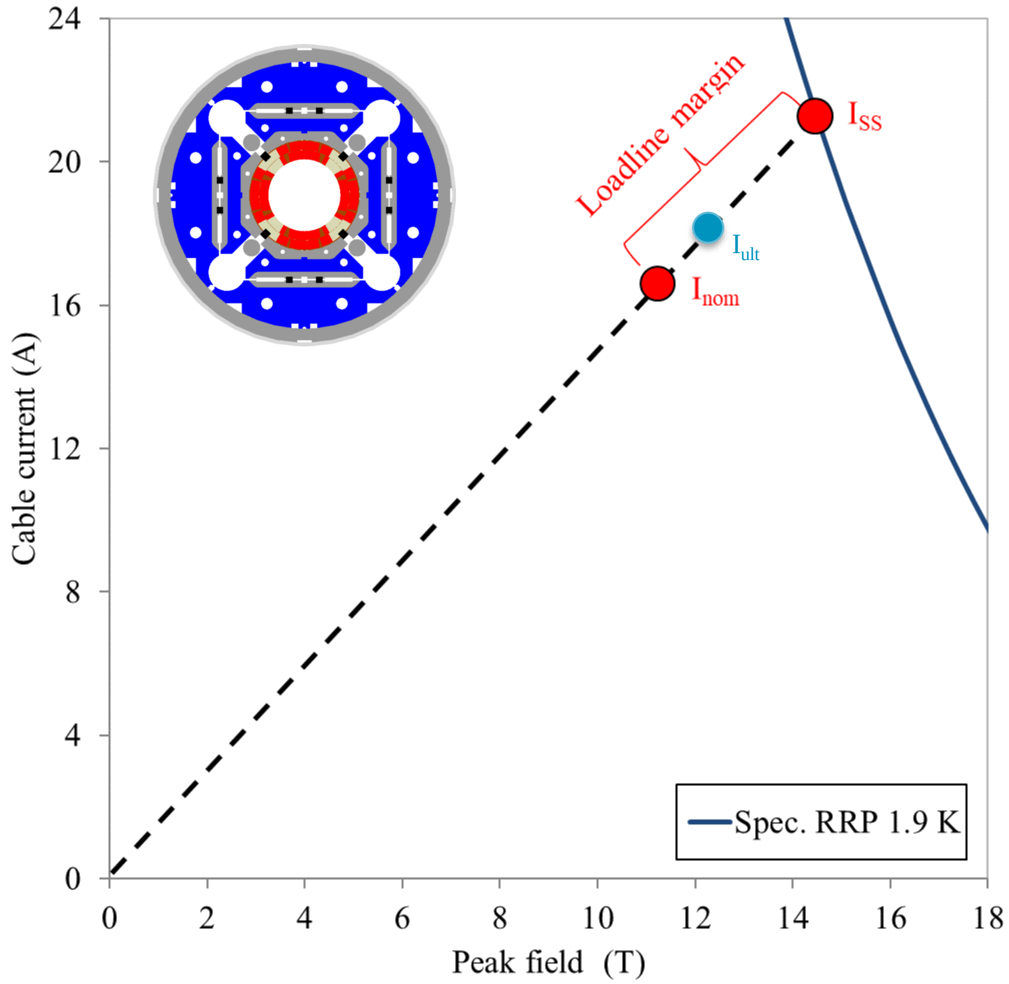
Introduction
Magnet design

- 150 mm aperture
- Double layer coil
  - wound with 18 mm wide cable, 0.85 mm Bruker-OST RRP strand
- Support structure based on aluminum shell
- Axial support with end-plate and axial rods
- Preload with bladders and keys



Introduction
Load-line and margin

- Requirement:
  - Nominal conditions (7 TeV operation)
    - G_{nom}=132.2 T/m
    - 11.3 T B_{peak_nom}
    - ~77% of I_{ss}
    - I_{nom}= 16230 (+300) A (*acceptance*)
- To check margin, short models pushed to
  - Ultimate conditions (7.5 TeV operation)
    - G_{ult}=142.1 T/m
    - 12.1 T B_{peak_ult}
    - ~83% of I_{ss}
- Instead, still to check margin, long magnets are ramped to I_{nom} at 4.5 K (~85% of I_{ss})



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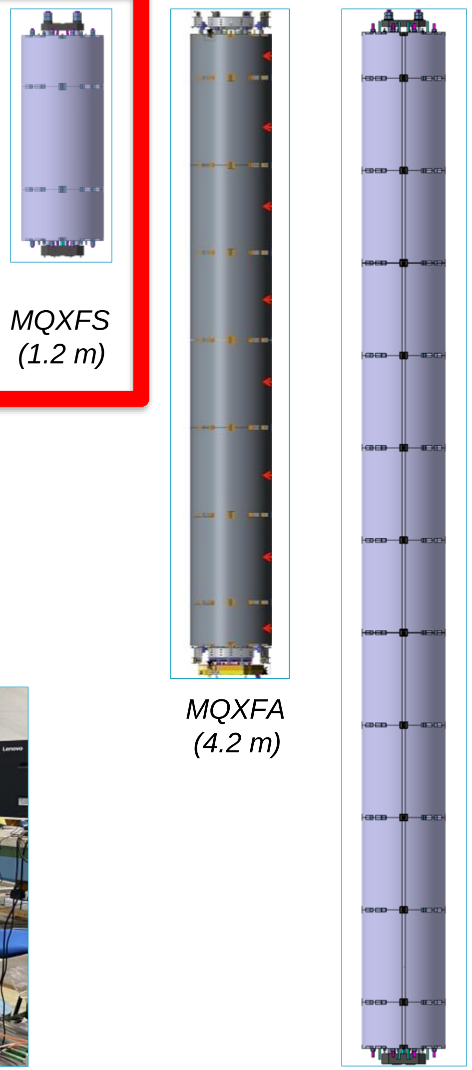
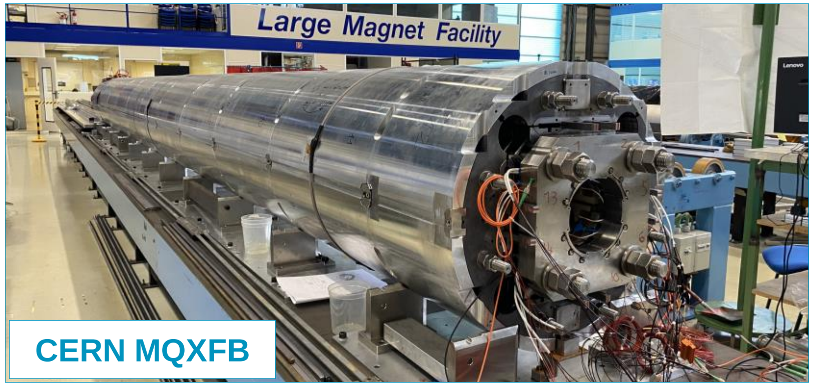


MQXFS (1.2 m)

MQXFA (4.2 m)

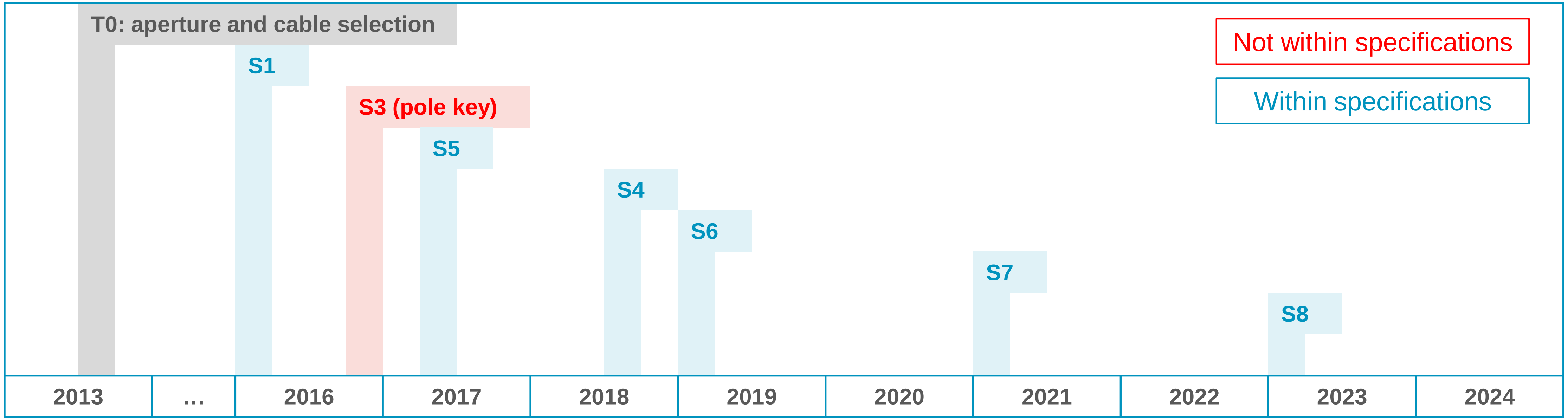
MQXFB (7.2 m)



- Different lengths, same design, very similar assembly procedure and loading target

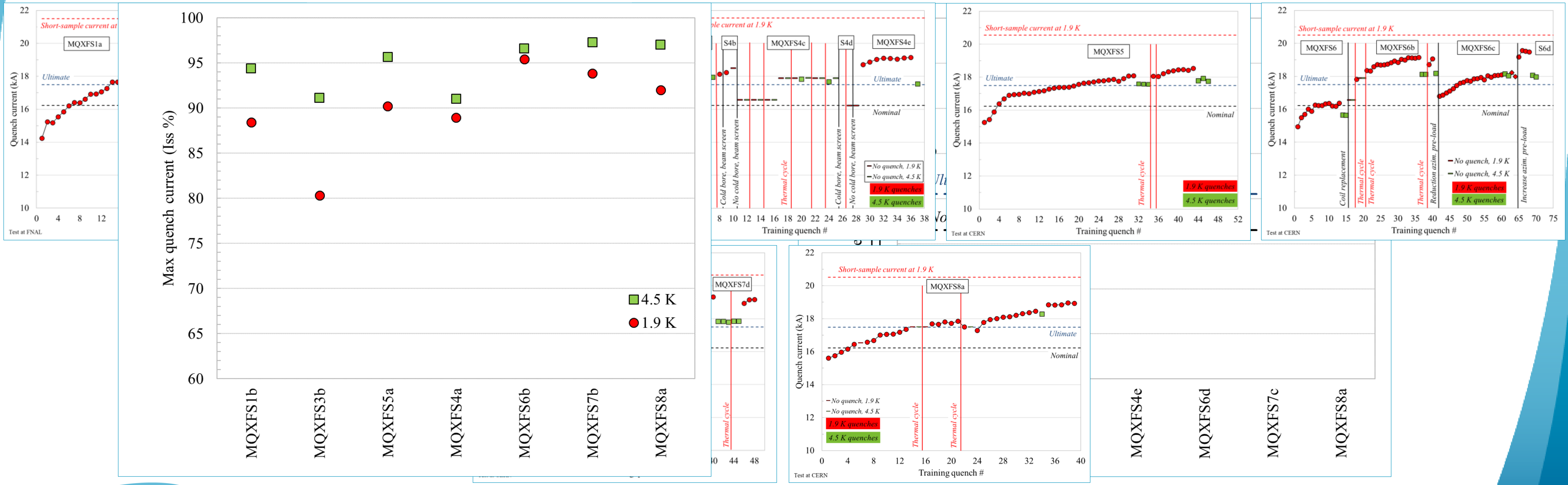
MQXFS timeline and test status

- First test ~ 3 years after decision on aperture and cable geometry
- 7 magnets fabricated and tested
- 27 coils tested, 4 different conductors
- Program still ongoing: initially, design and parameter validation; now technological studies



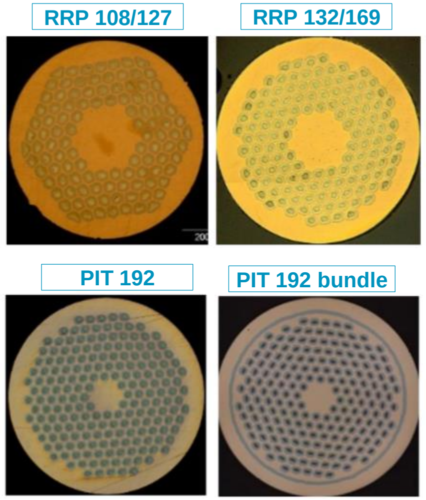
MQXFS performance reproducibility and margin

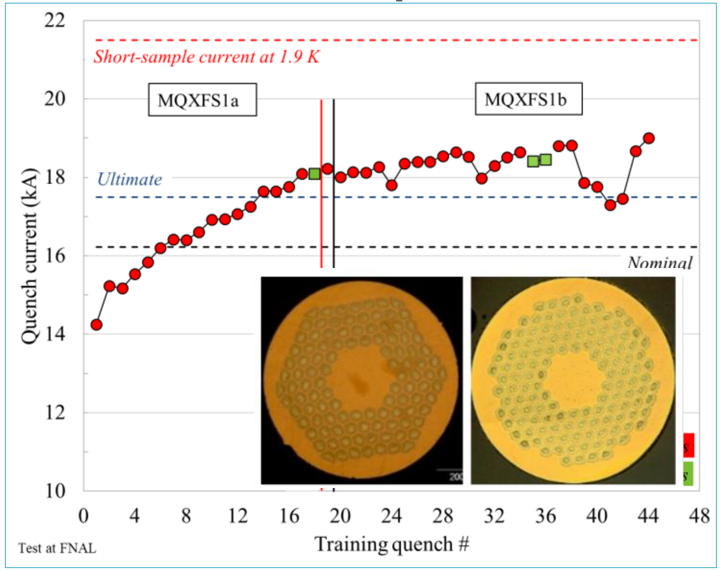
- All the 7 magnets passed nominal, all but S3 passed ultimate.
- Except S3, all reached 90-95% of I_{ss} at 1.9 K and 4.5 K, and the 13 T field level
  - 1.7 T more than required

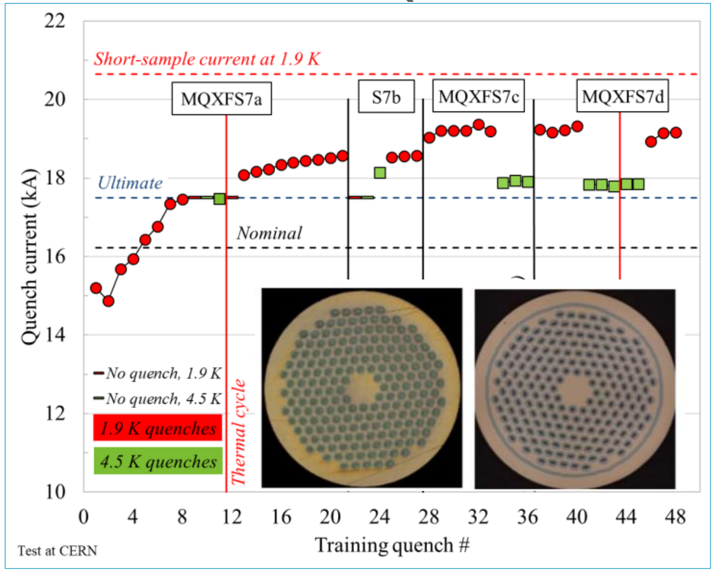


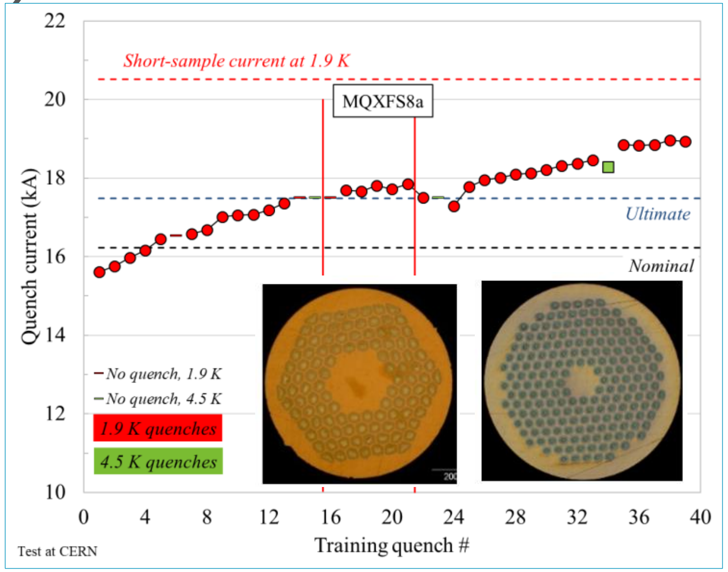
MQXFS: superconductor validation

- 4 Bruker-OST strands used during the short
  - RRP 108-127 chosen for the project
    - Sufficiently small filament and lower cost
  - In addition
    - RRP 132/169, PIT 192, and PIT 192 with bundle barrier
- Ultimate passed with all strands (also mixed)



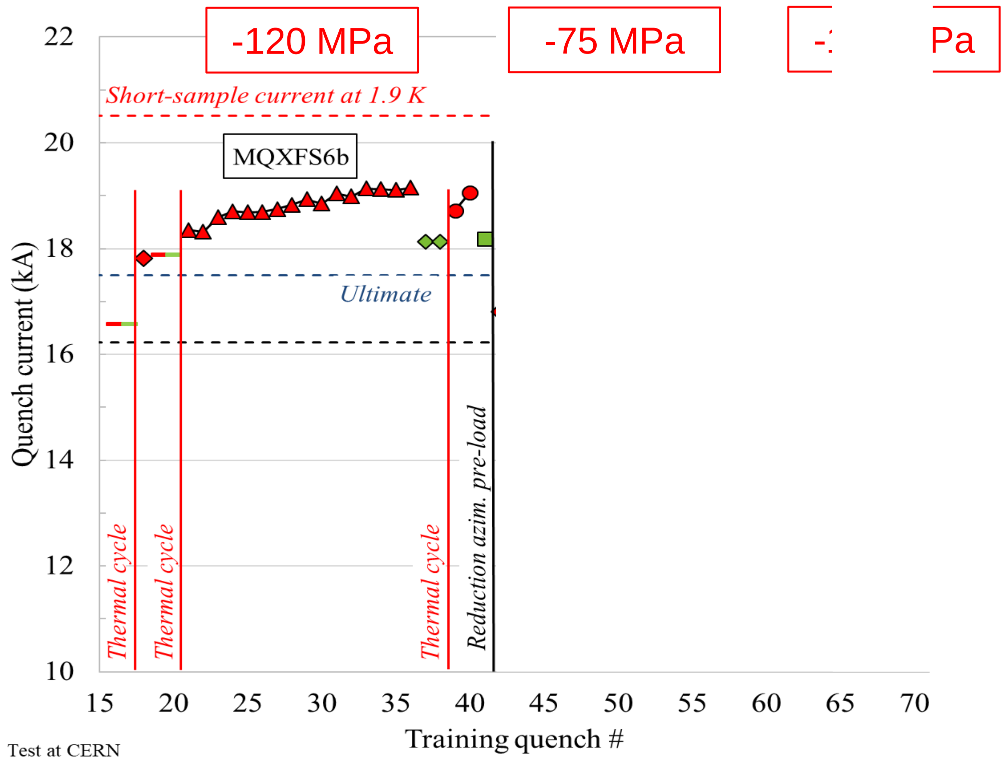






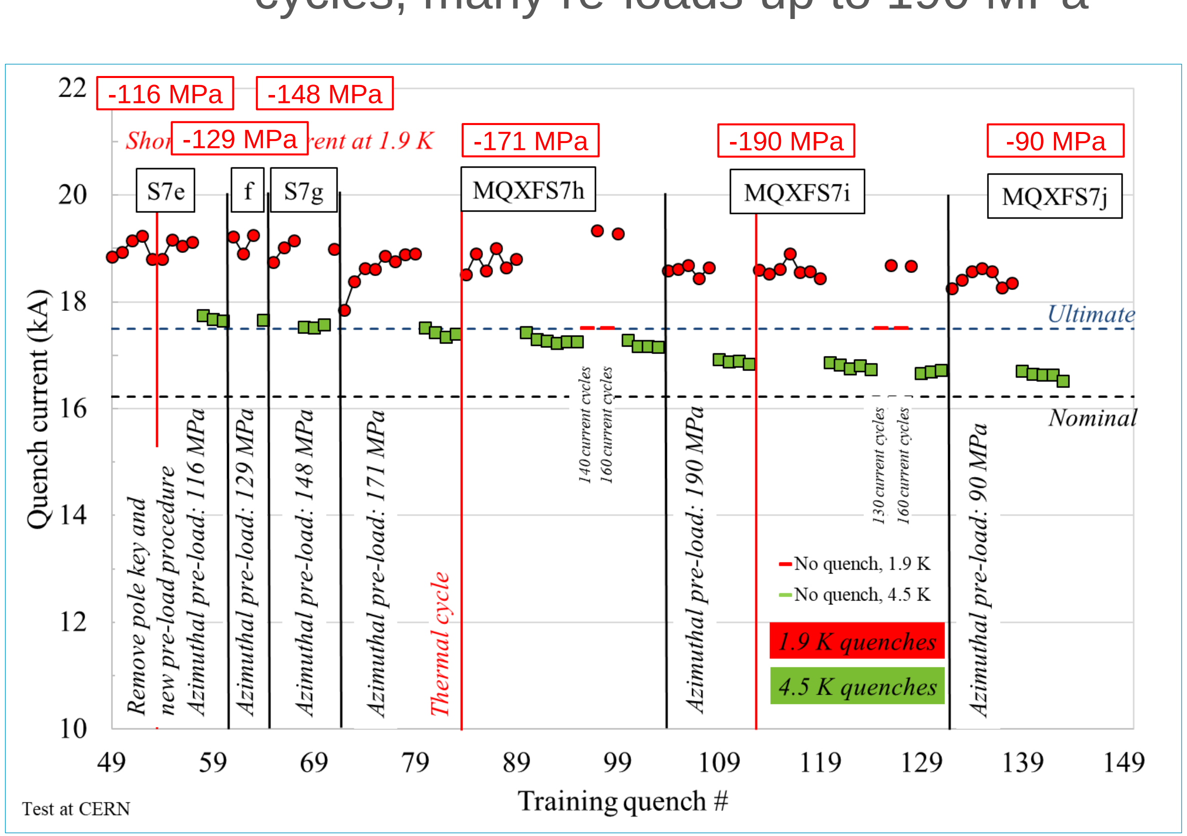
MQXFS: training/plateau vs. pre-stress

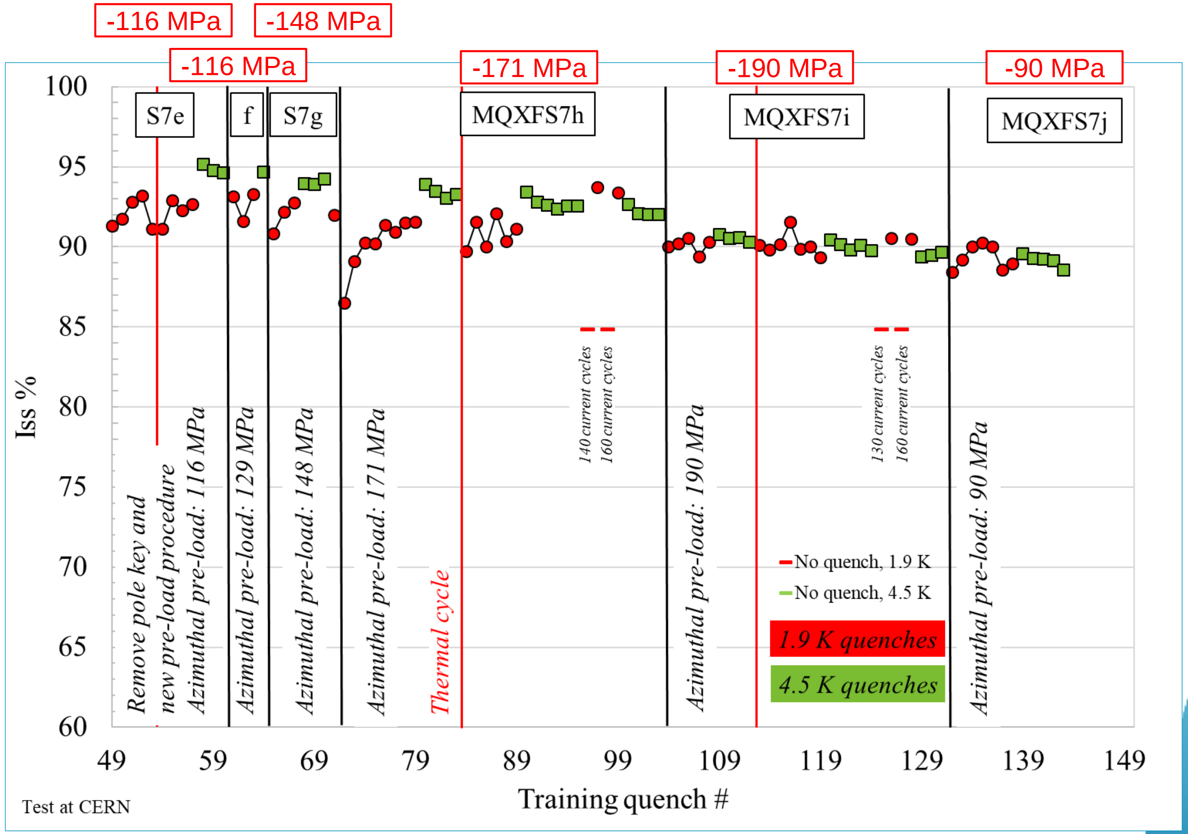
- Impact of pre-stress on training/plateau investigated with MQXFS6
- Wide pre-load window to reach ultimate current (-75 to -120 MPa)
- Indication that larger preload is beneficial to reach higher plateau 90% of I_{ss}



MQXFS: pre-stress limits

- Impact of pre-stress at 1.9 K on maximum current studied with MQXFS7 (PIT and RRP)
  - Some degradation appears in the PIT conductor in the 170-190 MPa range
  - No degradation observe in RRP up to 190 MPa in the 85% of I_{ss} level
  - Magnet above ultimate (and above 85% of I_{ss}) after 150 quenches, 600 power cycles, 14 thermal cycles, many re-loads up to 190 MPa





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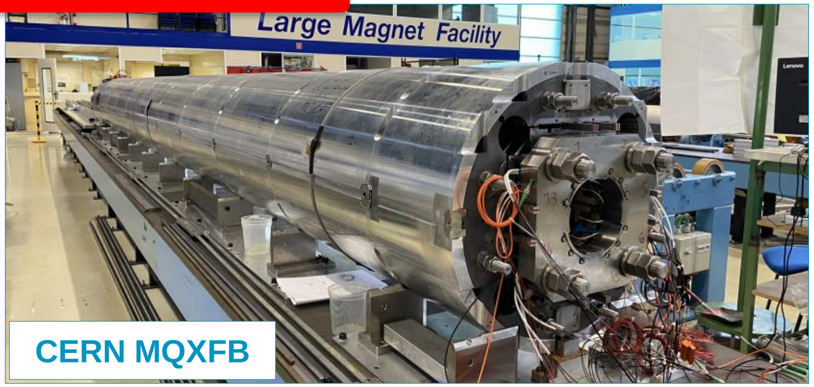
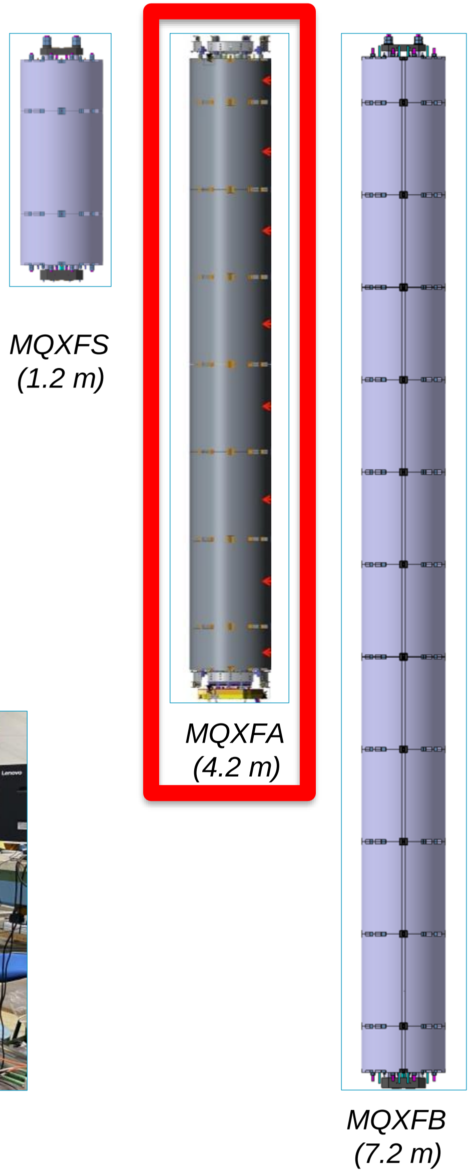


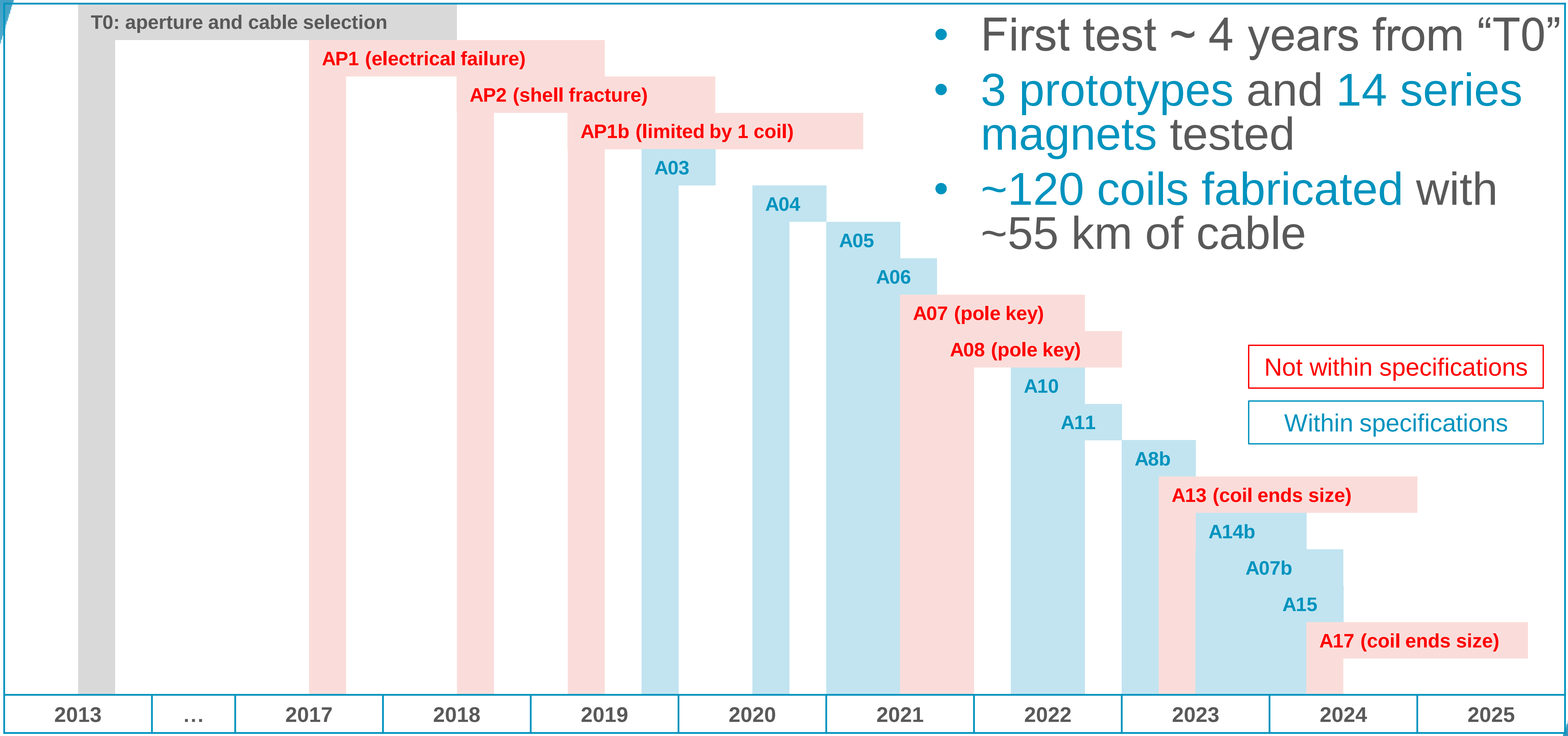


- Different lengths, same design, very similar assembly procedure and loading target

HiLumi HL-LHC PROJECT
US HL-LHC AUP
CERN

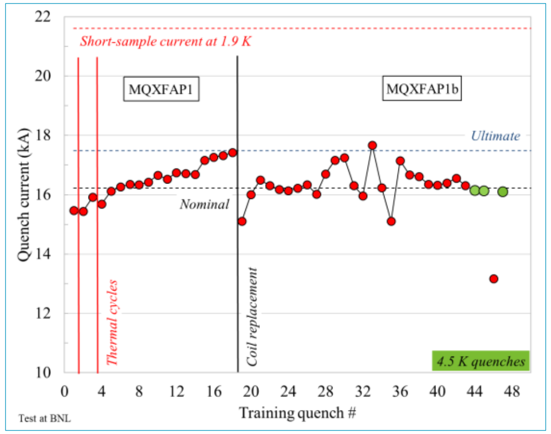
MQXFA timeline and test status

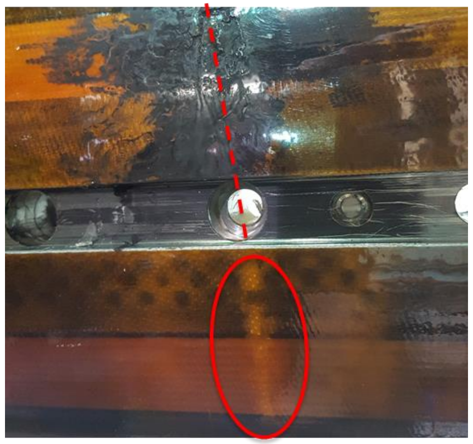
- First test ~ 4 years from “T0”
- 3 prototypes and 14 series magnets tested
- ~120 coils fabricated with ~55 km of cable

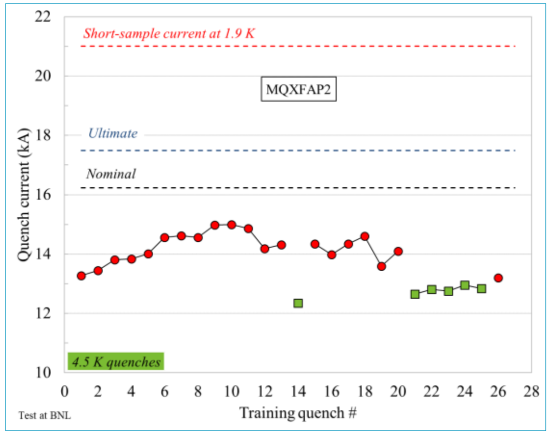


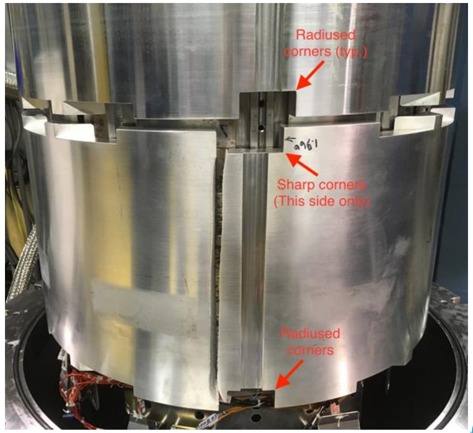
MQXFA prototype performance issues

- First 3 prototypes were limited by
  - AP1: a coil-heater double short caused by warm Hi-Pot performed well above Electrical Design Criteria
    - Reached ultimate before the short
  - AP1b: one coil performance
    - Possibly due to epoxy impregnation issue
  - AP2: a structural failure of one of the aluminum shell
    - Issue: non-conformity (sharp corners) in one of the shell
- Action items
  - Develop and follow-up of
    - Structural Design Criteria based on Failure Assessment Diagram
      - Improved inspections of structural components
    - Electrical Design Criteria
      - <u>In particular at warm temperature after Lhe exposure</u>
  - Review of impregnation process



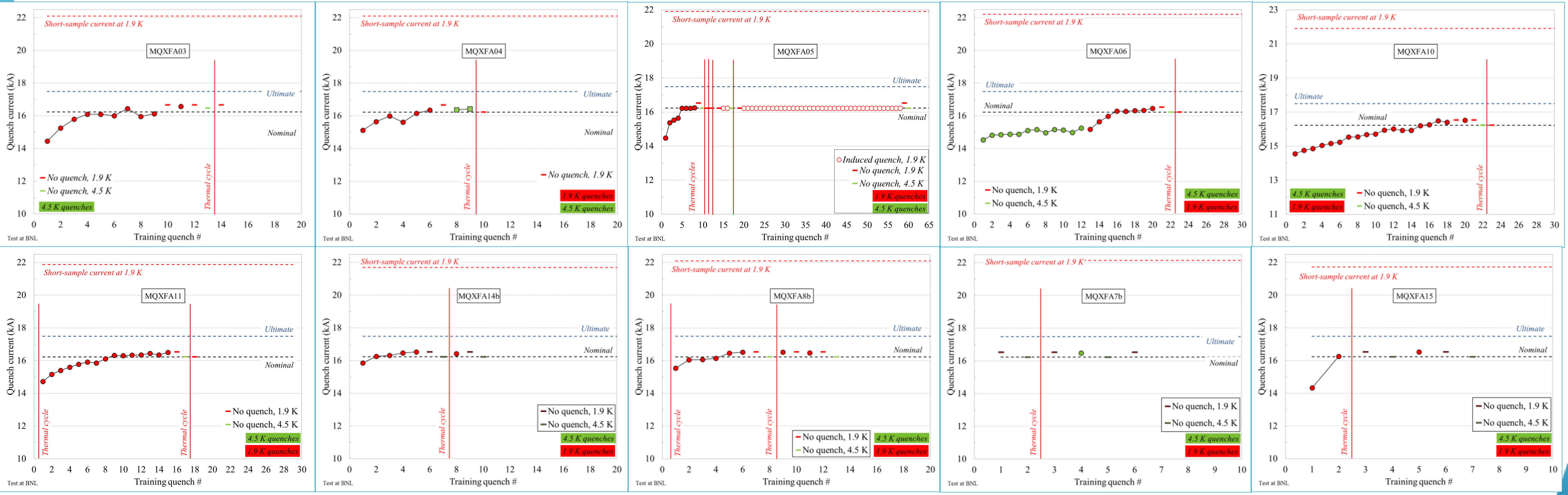






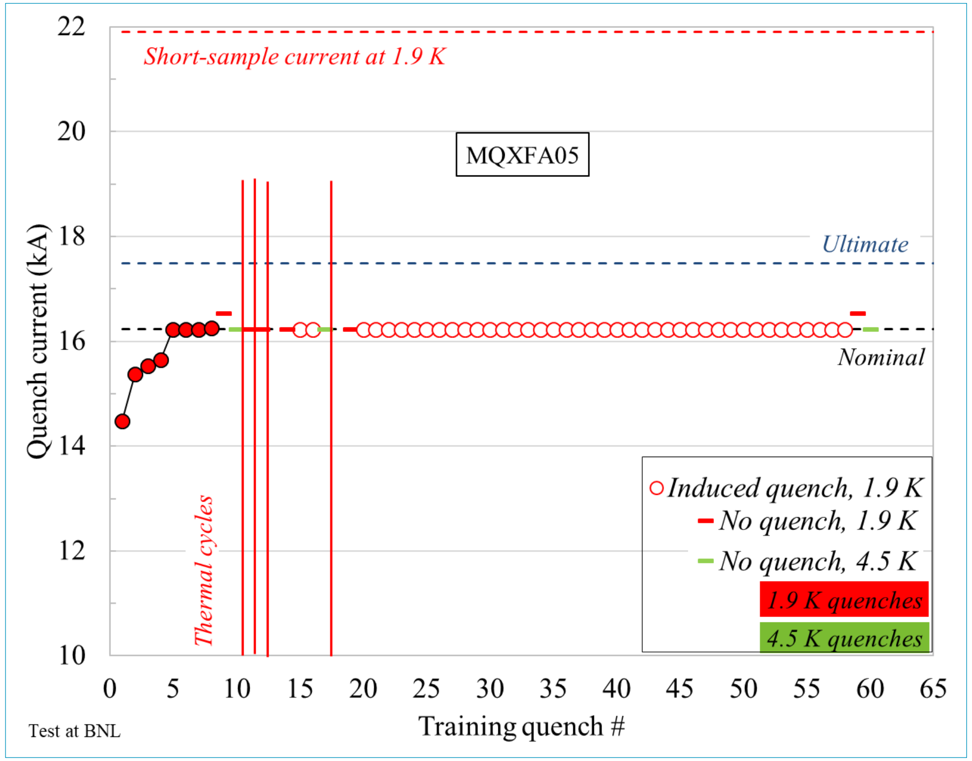
MQXFA series magnet performance

- 10 magnets hold acceptance current at 1.9 K, and nominal at 4.5 K
- Excellent memory after thermal cycle→ no re-training needed
- Nominal reached usually in <=10 quenches
- 3 successful magnets after replacing a limiting coil (disassembly/re-assembly)



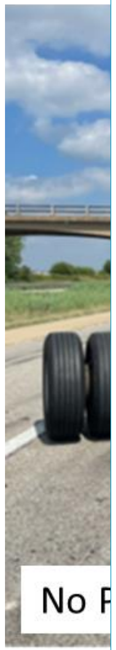
MQXFA series magnet performance

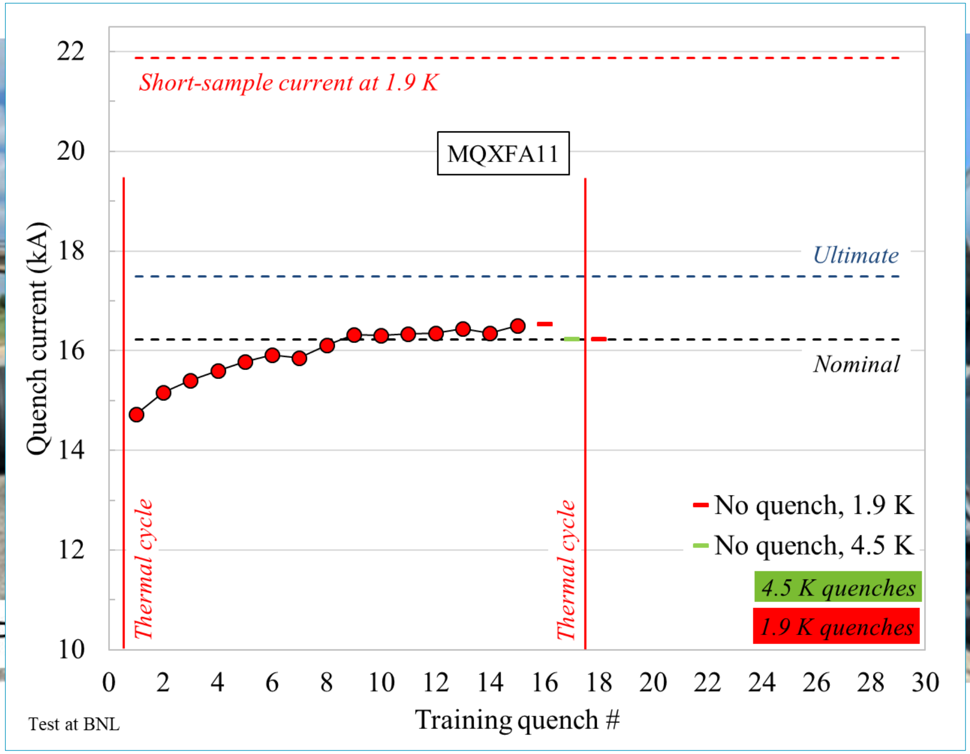
- Endurance
  - 5 thermal cycles, 52 quenches (42 induced)
  - No degradation observed



MQXFA series magnet performance

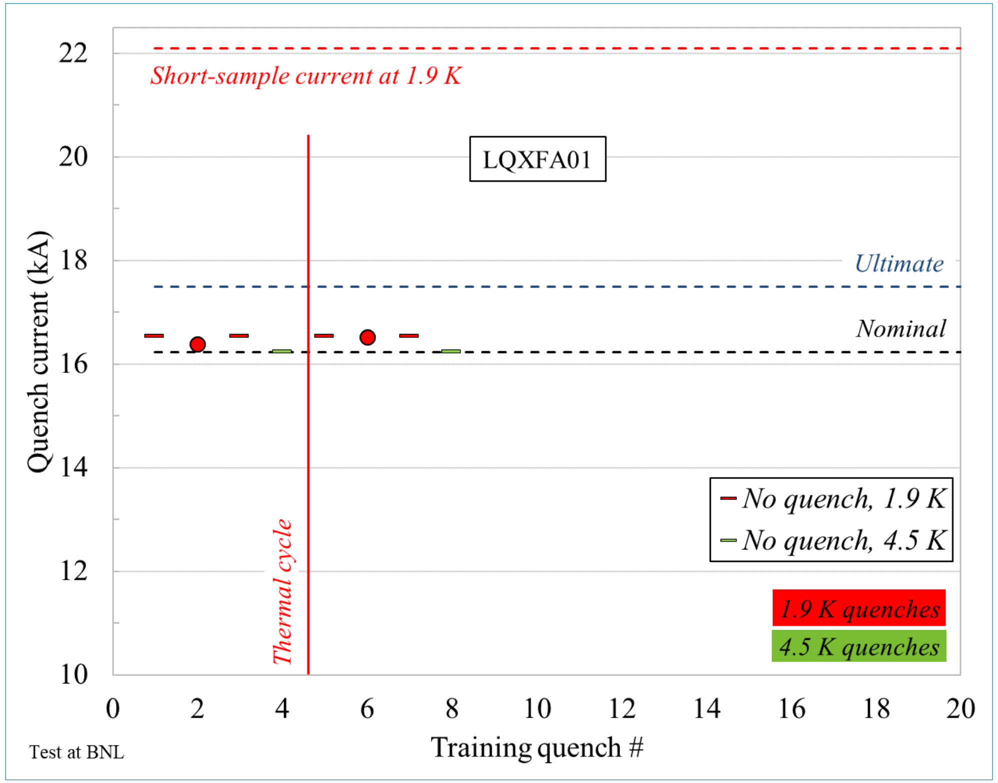
- Unplanned "resilience" test (MQXFA11)
  - …during the trip LBNL-BNL → "10 g"





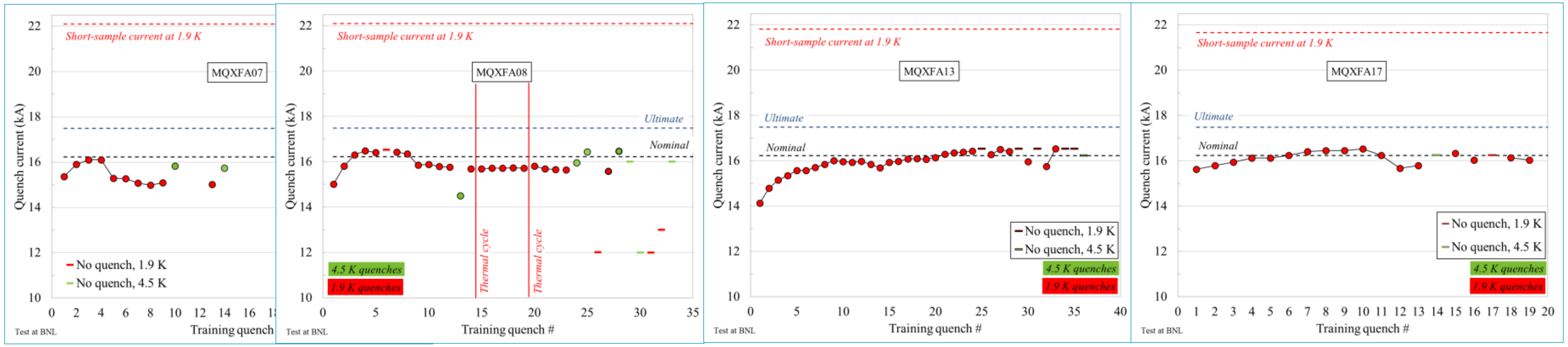
MQXFA series magnet performance

- First cold mass reaching performance with magnets A03 and A04 without training

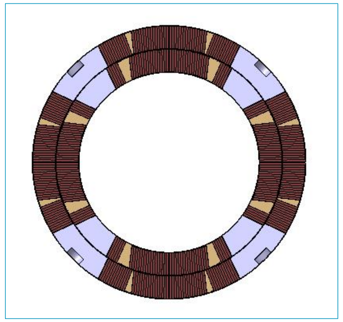


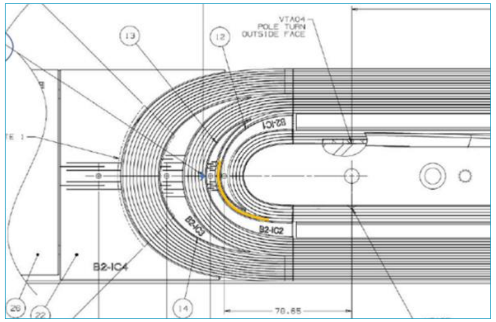
MQXFA series magnet performance

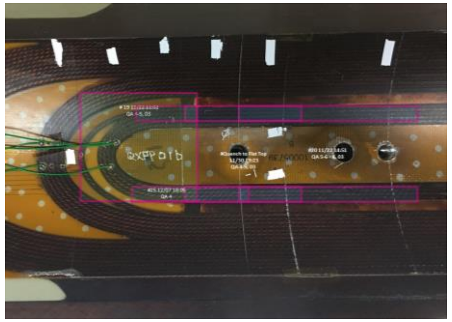
- 4 magnets with the MQXFA “disease”
  - De-training after few training quenches



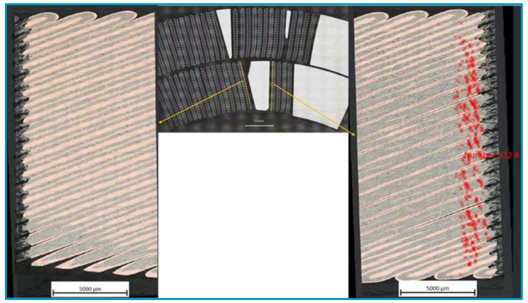
- Limited in the end region
  - Transition wedge to end-spacer





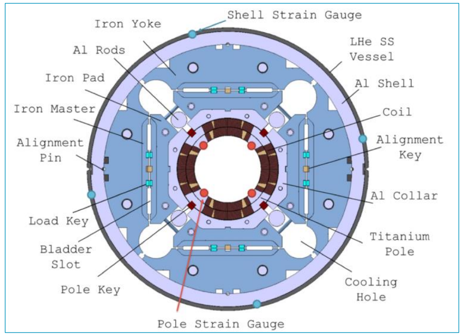


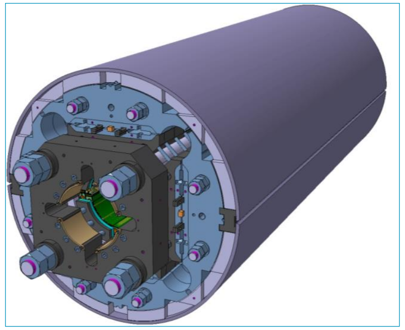
- Post-mortem metallurgical analysis indicated broken filaments in the quenching area

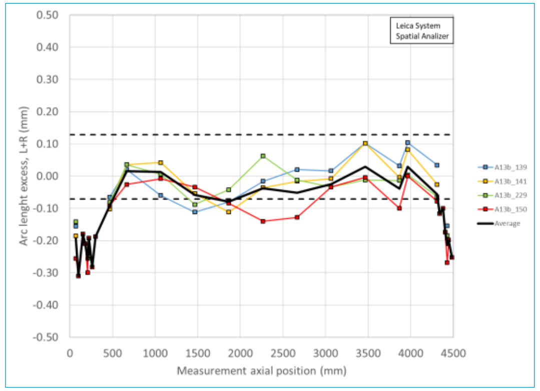


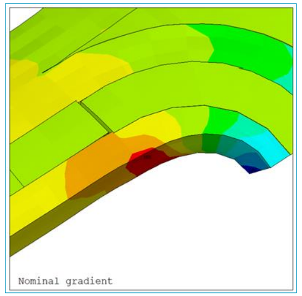
MQXFA series magnet performance

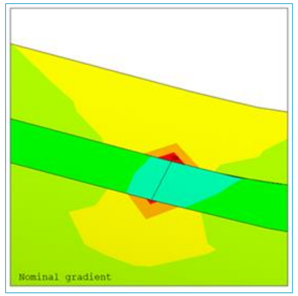
- Our current understanding and action times
  - Effect of axial Lorentz forces in the coil end region
- By design, axial forces counteracted by end support structure
  - axial loading (end-plate) + azimuthal loading (friction with support structure)
- Lack of end support caused by
  - Pole key interception of azimuthal loading (A07-08)
  - Coil significantly smaller in the end (A13-17)
- High axial strain in turn close to the transition
- Action items
  - Larger pole gap introduced
  - Increase overall pre-load and tapered shims
- So far, out of spec magnets fixed with coil replacement and improved pre-load











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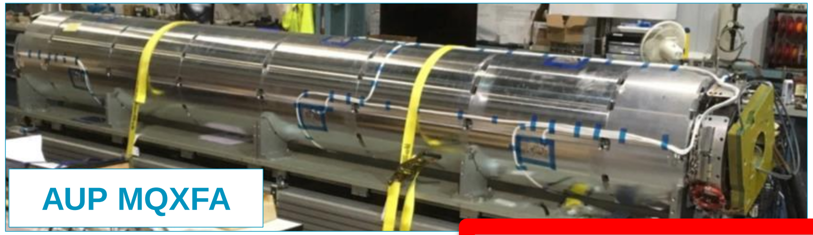
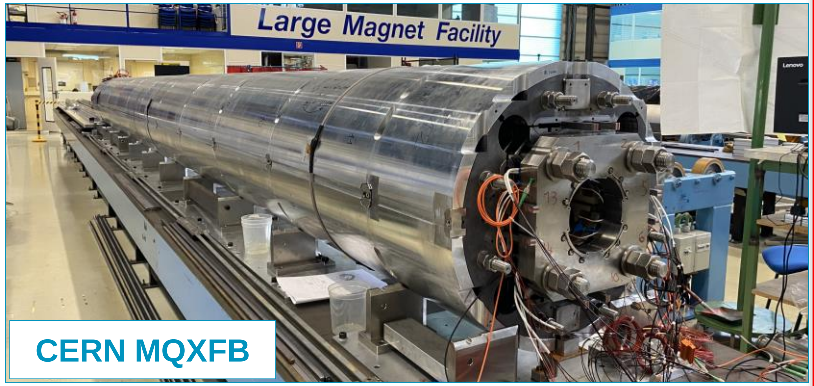
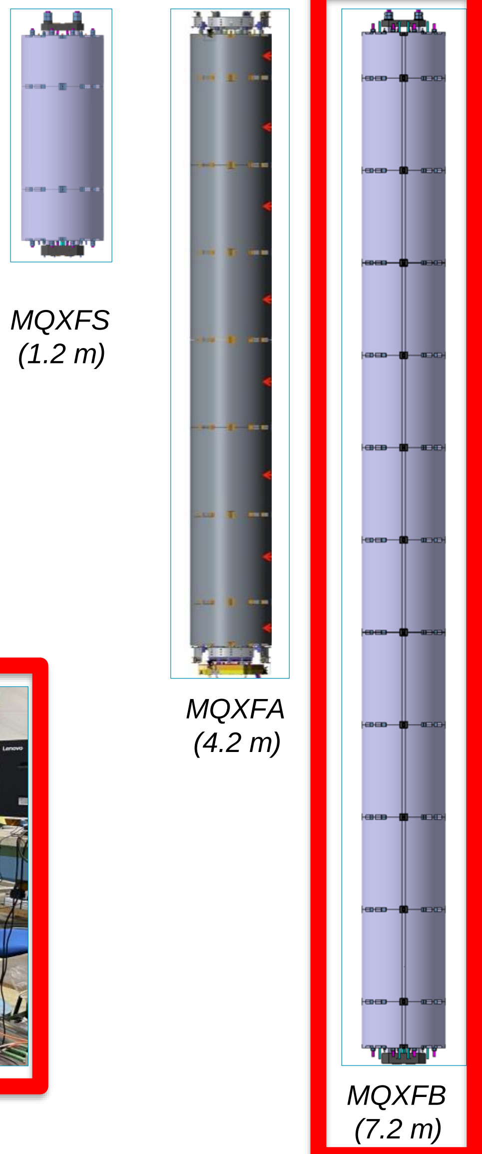


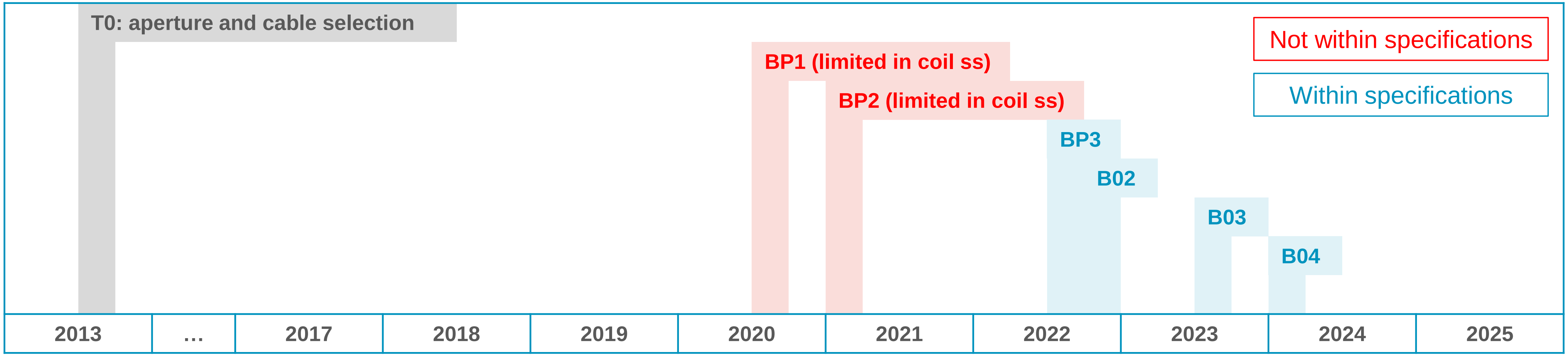




- Different lengths, same design, very similar assembly procedure and loading target

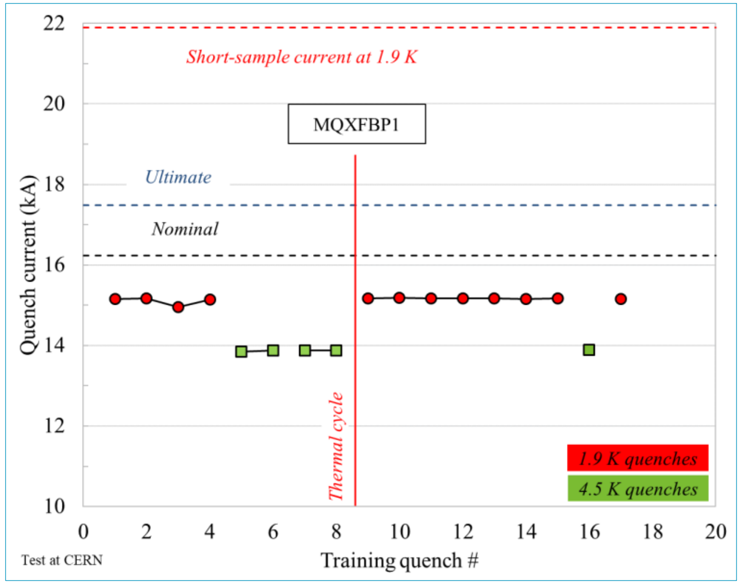
MQXFB timeline and test status

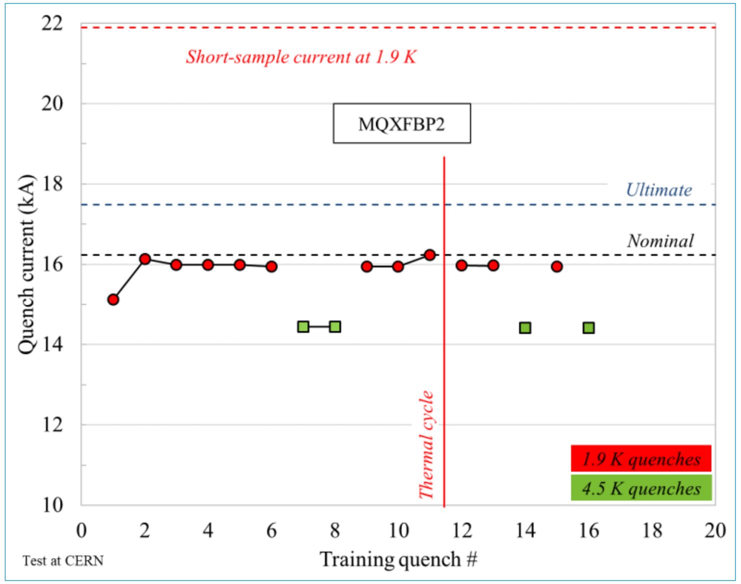
- First test ~ 7 years after decision on aperture and cable geometry
  - Full cold mass !
- 3 prototypes and 3 series magnets tested
- ~60 coils fabricated (ongoing)→ wound with ~45 km of cable

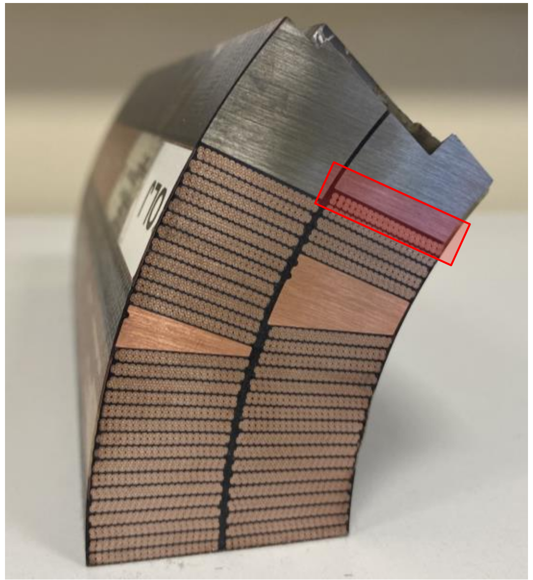


MQXFB magnet performance

- The first two MQXFB prototype magnets limited below nominal current at 1.9 K.
  - 4.5 K behaviour compatible with magnet on the critical surface → reached conductor limits
- In all the cases, the quench location was on the inner layer pole turns near the centre of the magnet.
- Post-mortem metallurgical analysis indicated broken filaments in the quenching turns

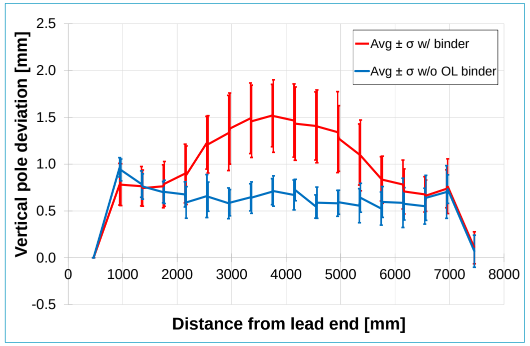






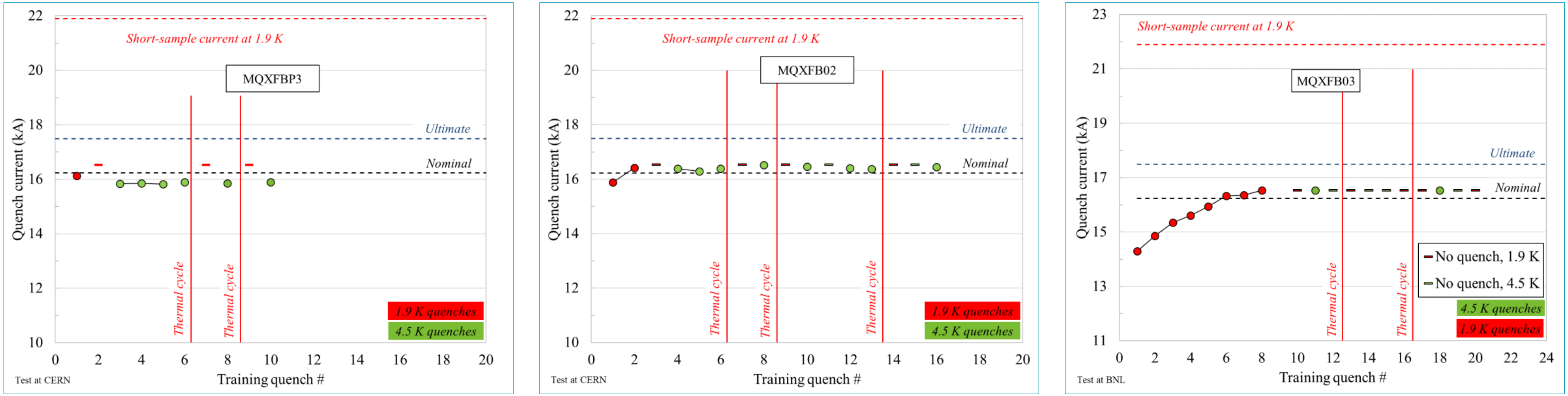
MQXFB magnet performance

- Corrective strategy: focus on reducing strain in the conductor during coil fabrication and magnet assembly
- Three steps
  1. Reducing the stress induced on the coil during ss shell welding
  2. Reducing the peak stress in the coil during bladder operation
  3. Providing more room the coil in the reaction fixture during heat treatment
     1. Uniform coil size along the length



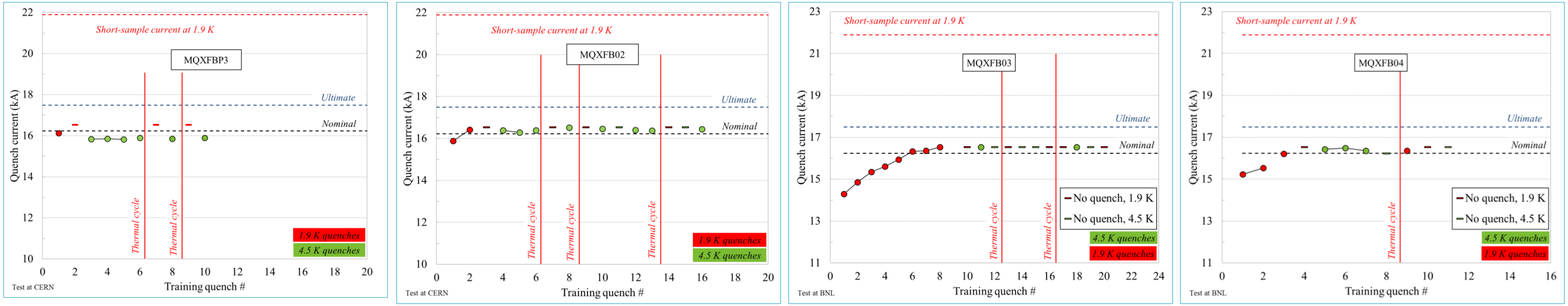
MQXFB magnet performance

- The corrective strategy was progressively implemented in the following 3 magnets
- BP3 reached accept. at 1.9 K (but not at 4.5 K), B02 reached accept at 1.9-4.5 K (still signs of degradation) and B03 without any sign of degradation



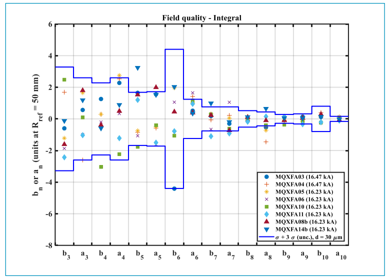
MQXFB magnet performance

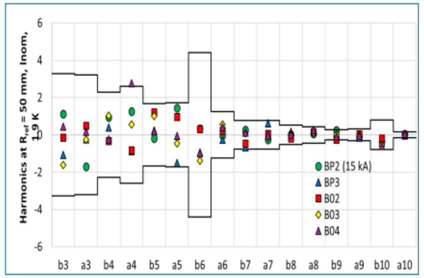
- 4 consecutive magnets reached acceptance at 1.9 K
  - The last 3 reached acceptance also at 4.5 K
- Nominal reached in few quenches
- Excellent memory after thermal cycle→ no need of retraining
- Endurance test in B02 showed no degradation after 3 thermal cycles, ≈ 50 quenches and 500 current cycles.

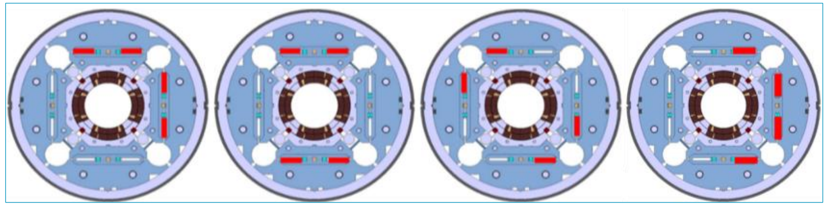


Field quality and quench protection

- Accelerator field quality reached by both MQXFA-B
  - When needed, magnetic shims inserted to correct un-allowed harmonics
- Two quench protection systems performing as expected
  - Outer layer quench heaters
  - Coupling-Loss Induced Quench (CLIQ) System
- Magnet protected with stored energy density in the coil 50% higher than for LHC dipoles
  - And half of the time margin







Outline

- Introduction
- Short model program MQXFS
- AUP 4.2 m long MQXFA
- CERN 7.2 m long MQXFB
- **Conclusions**

Conclusions

- MQXF will be the first Nb_3Sn magnet installed in an accelerator
  - ….and the longest Nb_3Sn magnet (7.5 m long), and the first with a bladder-and-key support structure
- More than 200 coils fabricated in the 3 different sites, and 30 magnets (with re-loads…thermal cycles….change of coils…) → huge statistics for Nb_3Sn technology

- Short models with excellent performance
  - Ultimate reached with a very broad pre-load range (80-190 MPa)
  - Pre-load beneficial to training
  - Some degradation visible in the 170-190 MPa level, but only in the more sensitive conductor (still > I_{ult})
  - Excellent tools for further R&D on the 12-14 T field level.

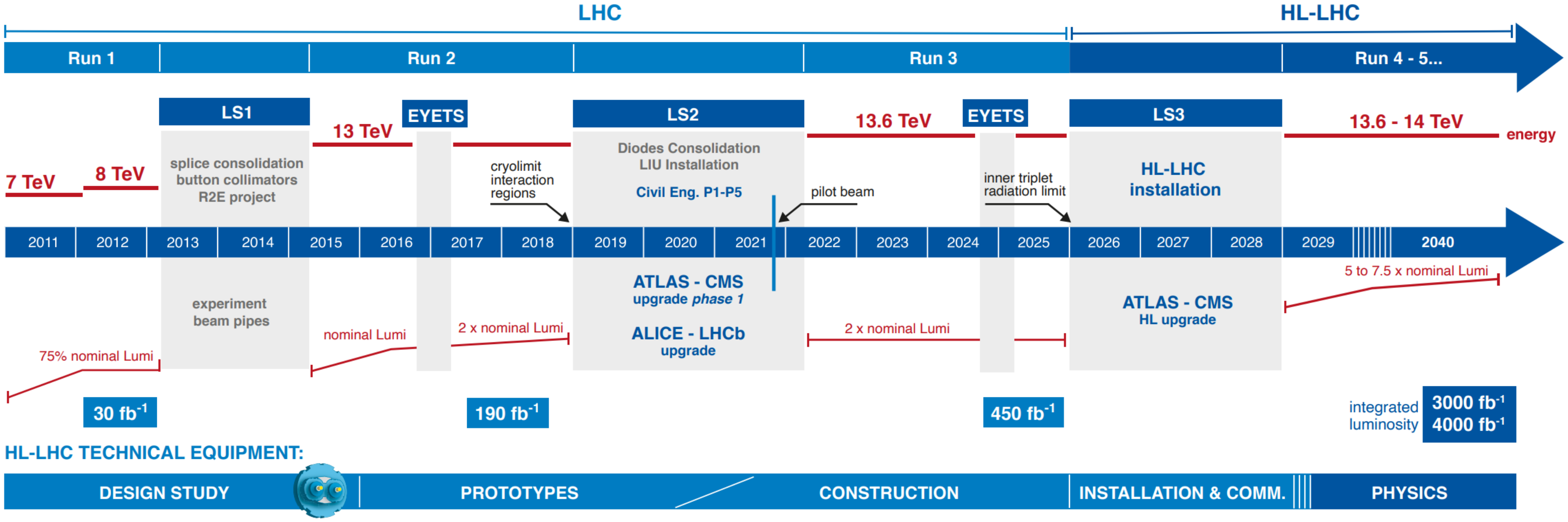
- In spec. long magnets: short training, excellent memory, no degradation after thermal-current cycles, with temperature margin, protected, and with good field quality

- Not in spec. long magnets: focus on
  - reducing conductor strain during magnet fabrication (MQXFB)
    - Coil free to move during reaction
  - reducing conductor strain during powering in the coil ends (MQXFA)
    - Coil not-free to move in the ends during excitation → coil-replacement and adjustment of pre-load

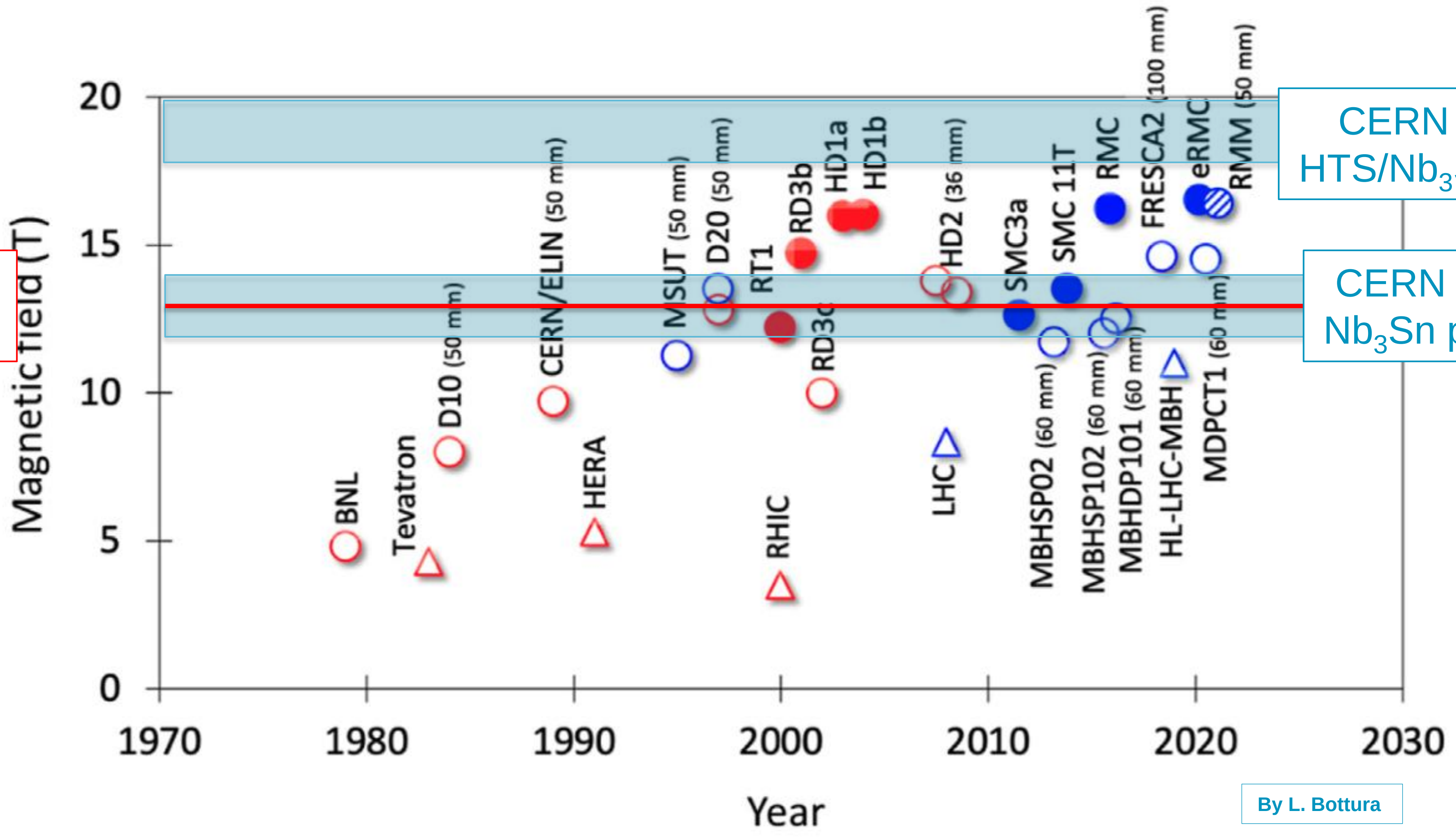
Appendix

Introduction
From LHC to HL-LHC

- HL-LHC goals
  - Extend LHC life time by 15+ years
  - Prepare the machine for producing in that period 10 times more data as compared to the nominal LHC operation period



Relevance to current magnet programs



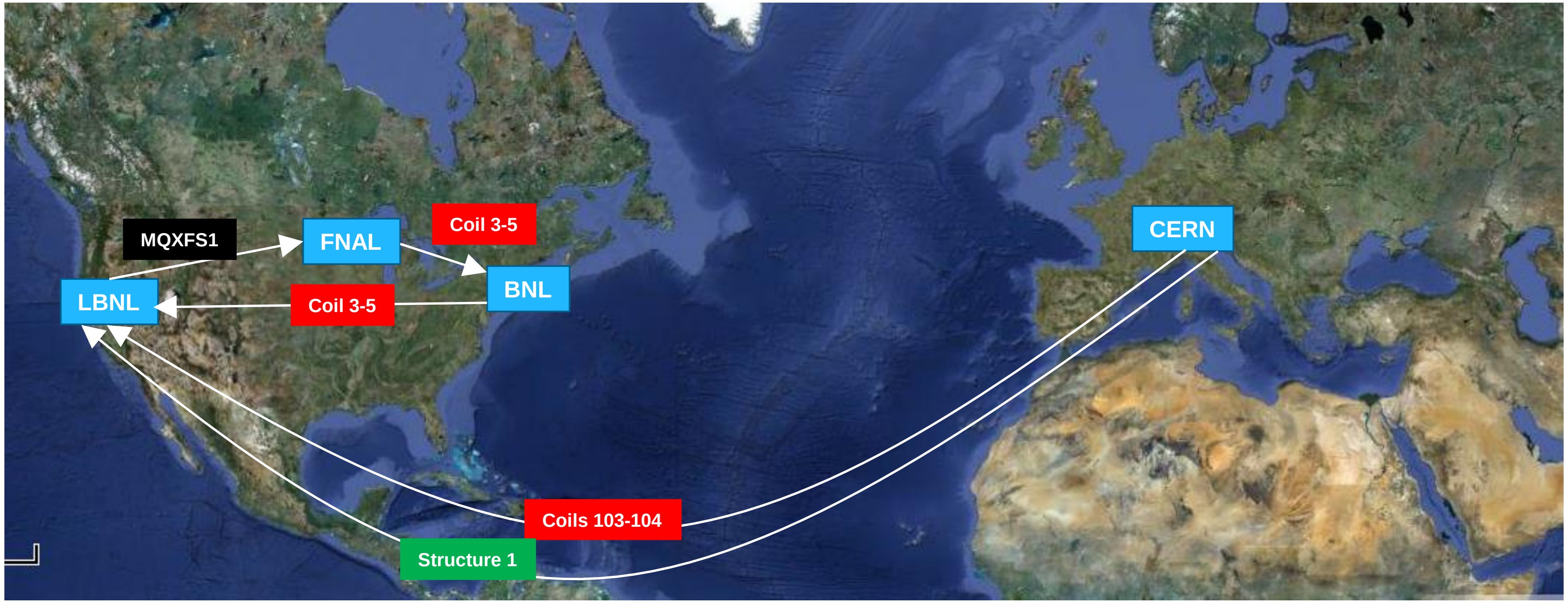
MQXF 13T

CERN HFM & US MDP HTS/Nb_3Sn program (~20T)

CERN HFM & US MDP Nb_3Sn program (12-14T)

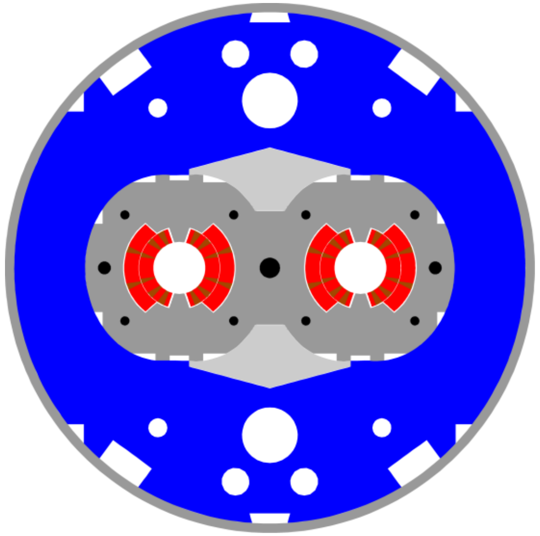
By L. Bottura

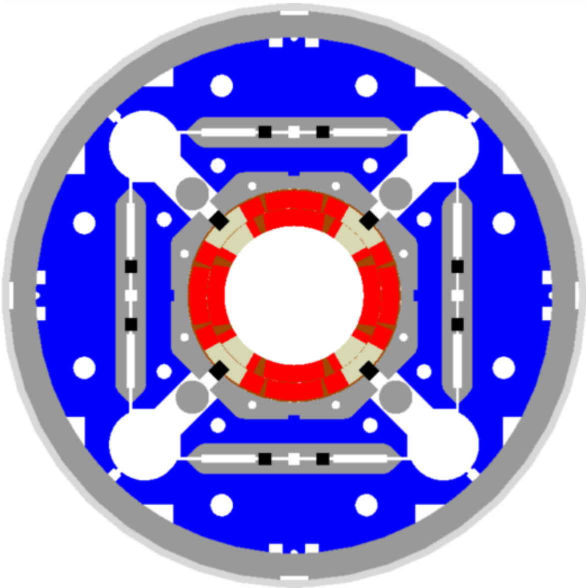
The early magnets
MQXFS1: the first one



- Designed and fabricated by multiple laboratories

Introduction
LHC dipole vs HL-LHC low-β quadrupole





- Nb-Ti
- 8.3 T
- $\sigma_{\theta\_e.m.}$= 50-60 MPa

- Nb_3Sn
- 11.3 T
- $\sigma_{\theta\_e.m.}$= 100-110 MPa

MQXFS7 from a mechanical point of view